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Signal Predictions for Mass Detection using a Cold Atom Gravity Gradiometer

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May 23, 2012

LLNL-PRES-558014

Motivating problem: Detection of shielded radioactive contraband in moving vehicles

- Radiation sensors can detect unshielded radioactive materials

- Shielding reduces radiation signature but increases the mass

- Gravimetry can measure changes in the gravitational acceleration caused by massive objects
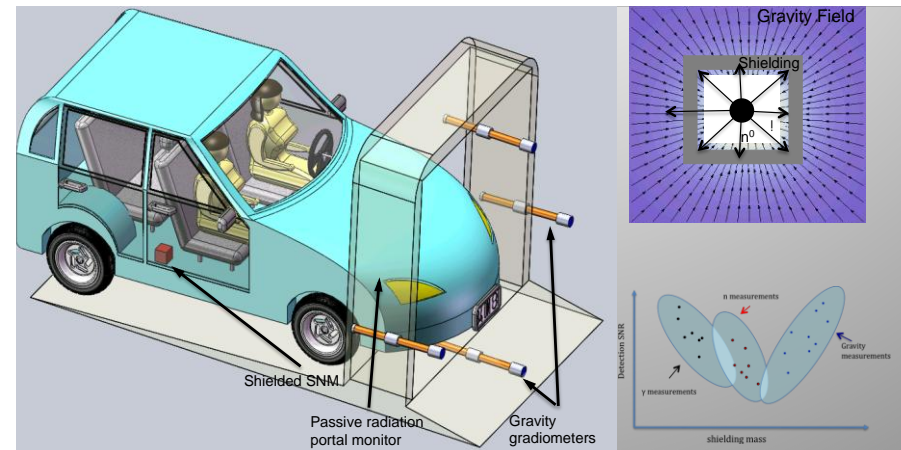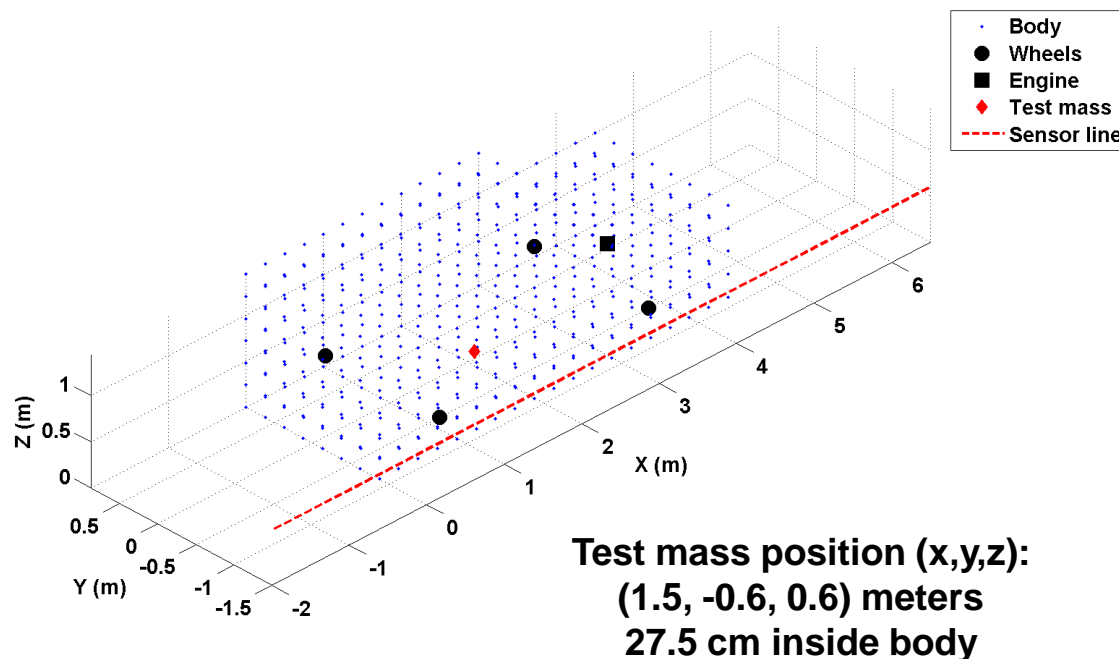
Signal processing problem

- Given data from an array of gravimeters and a model of a vehicle, determine whether an additional mass is present

- Basic equation for gravitational response is Newton's law

- Cold atom gravimeter responds to the local gravitational acceleration vector g and its gradient T (tensor)

Atom cloud phase difference $\triangle\phi \approx \boldsymbol{\alpha} \cdot \mathbf{g} + \boldsymbol{\beta} : \mathbf{T}$

Initial step is to determine the size of the perturbation caused by an object compared to the vehicle itself

Simple point mass model for car and added mass

- **Point mass mesh model for body (resolution ~10 cm, 524 points); overall dimensions of a Honda Civic**
- **Total mass, wheel mass, and engine mass obtained from Honda Civic specifications (http://automobiles.honda.com/civic-sedan/specifications.aspx)**
- **Sensor line 60 cm above ground and 63.5 cm from car body**

Test mass position (x,y,z): (1.5, -0.6, 0.6) meters 27.5 cm inside body

Mass table (kg)

Body	1048
Wheels	6 (each)
Engine	140
Test mass	45

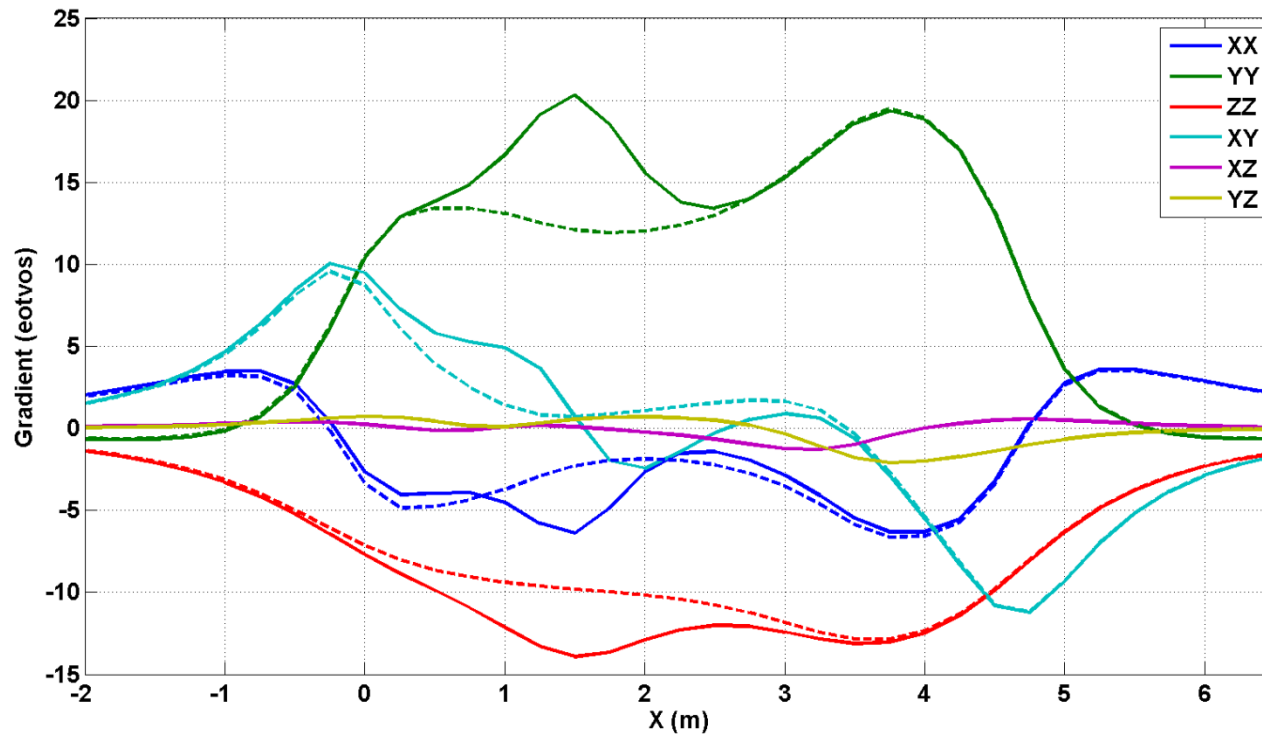**Total vehicle mass is 1212 kg**

Calculate gravitational acceleration with and without test mass

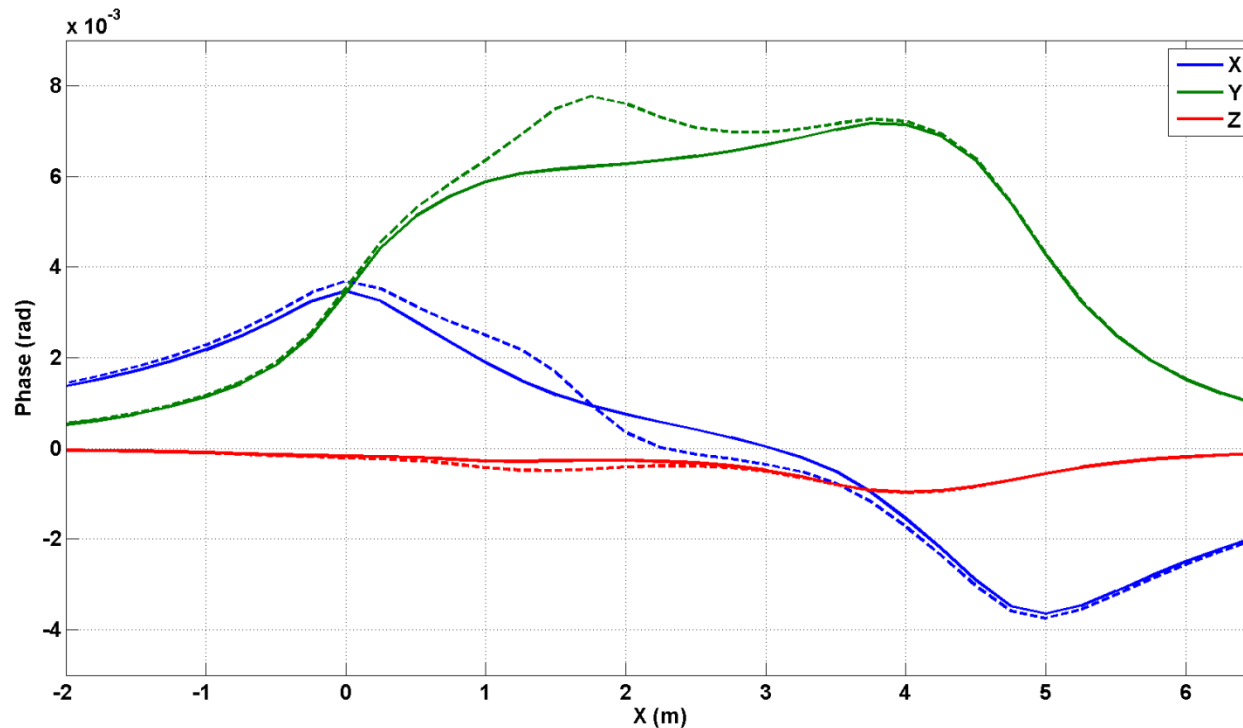$1 \text{ eotvos-m} \approx 10^{-10} \text{ g}$
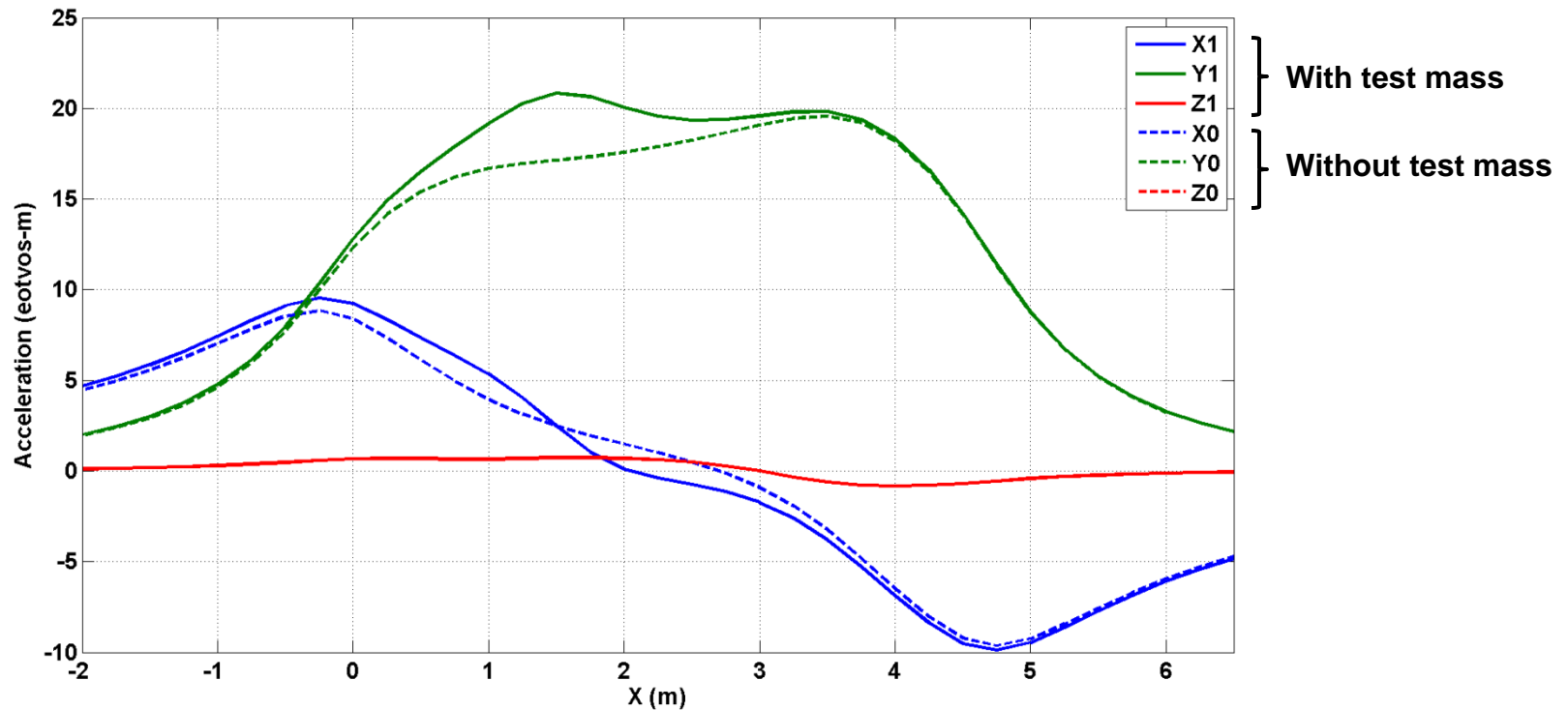
Gravity gradient tensor (6 components)

Solid lines: with test mass
Dashed lines: without test mass

Phase for 3 orthogonal sensors

**Solid lines: with test mass**
Dashed lines: without test mass

X: sensor in x direction
Y: sensor in y direction
Z: sensor in z direction

- **Launch velocity: 1.84 m/s upward**
- **Sensor interrogation time: 0.15 s**
- **Vehicle velocity: 5 MPH in +x direction**

Consider multiple sensor lines to explore spatial distribution of gravitational response

- **Point mass mesh model as before**
- **Place sensor lines at 20 cm intervals in a box surrounding the model**
    - **Upper box surface at height of 2 meters**
    - **Lower box surface at 0.6 meters below ground level**
    - **Sides of box at +/- 1.5 meters**
    - **All surfaces approximately 60 cm from sides**
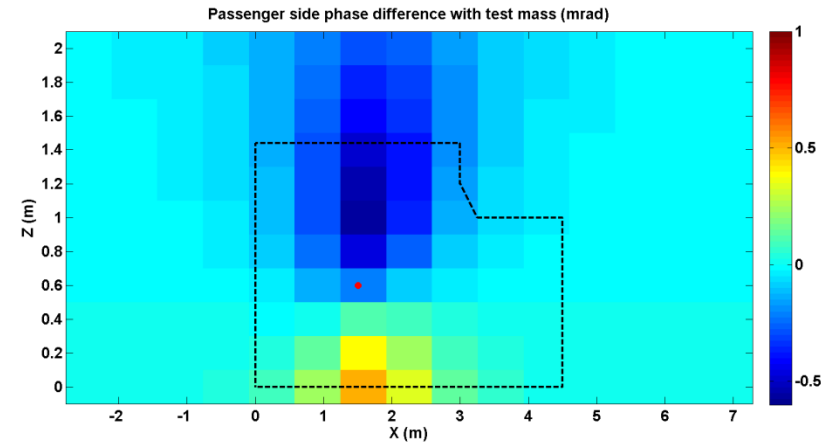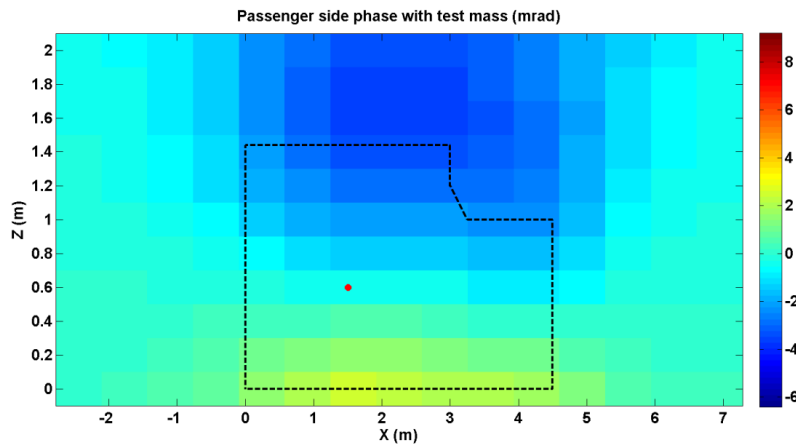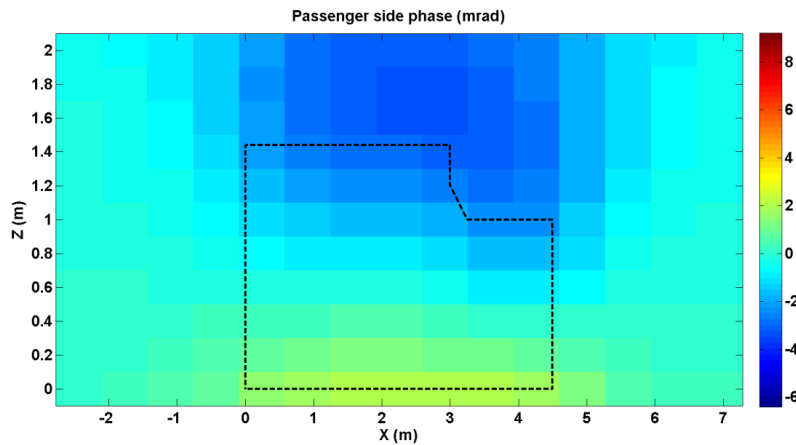   - **Sensor line sampling interval equivalent to 2 samples per second with vehicle moving at 3 MPH**
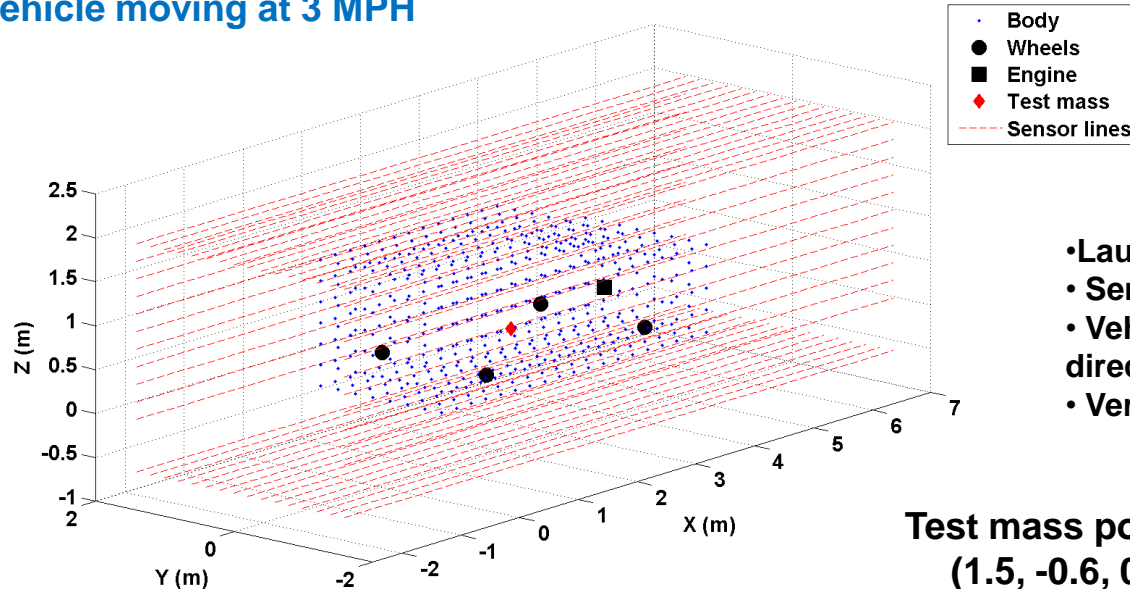
Gravimeter model parameters:

- Launch velocity: 1.84 m/s upward
- Sensor interrogation time: 0.15 s
- Vehicle velocity: 3 MPH in +x direction
- Vertical sensors

Test mass position (x,y,z):
(1.5, -0.6, 0.6) meters
27.5 cm inside body

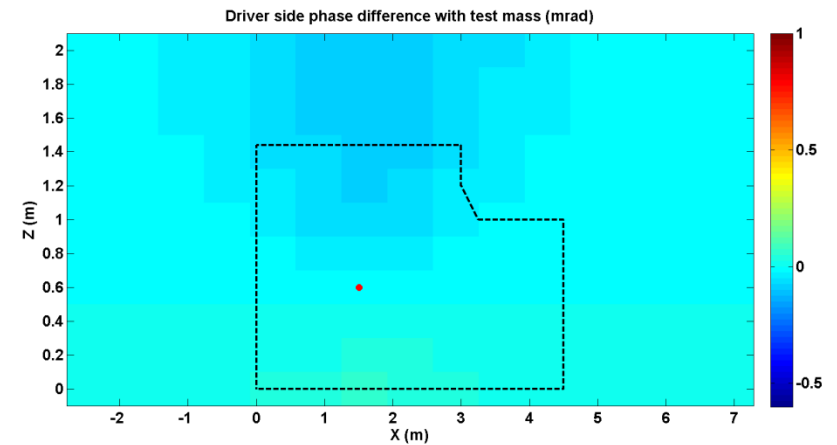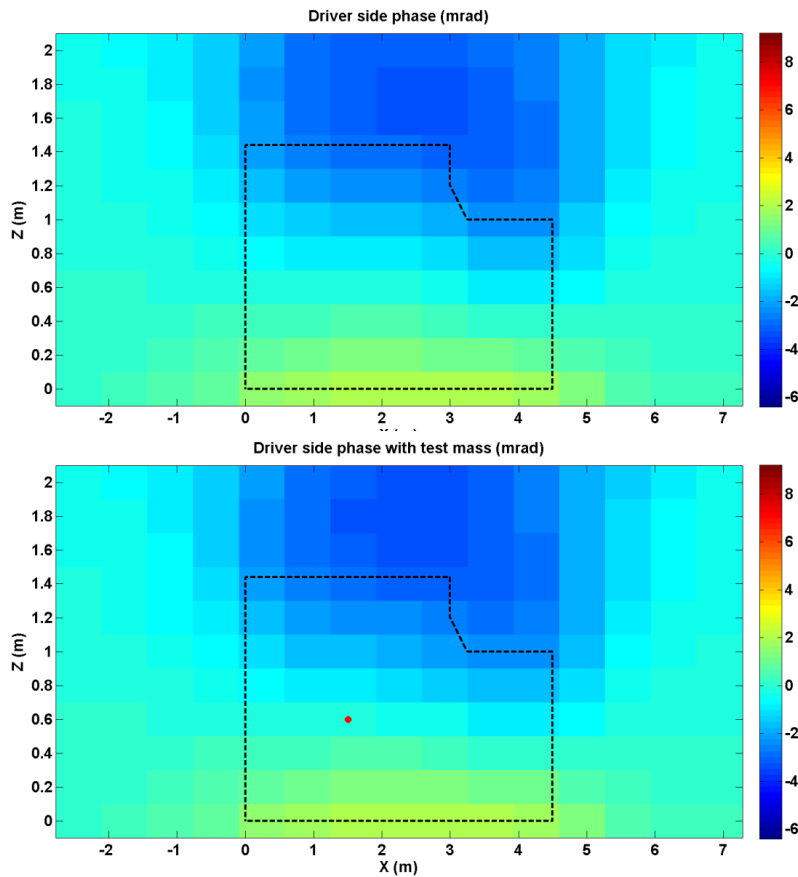# Passenger side phase (mrad)

Dotted line is outline of vehicle
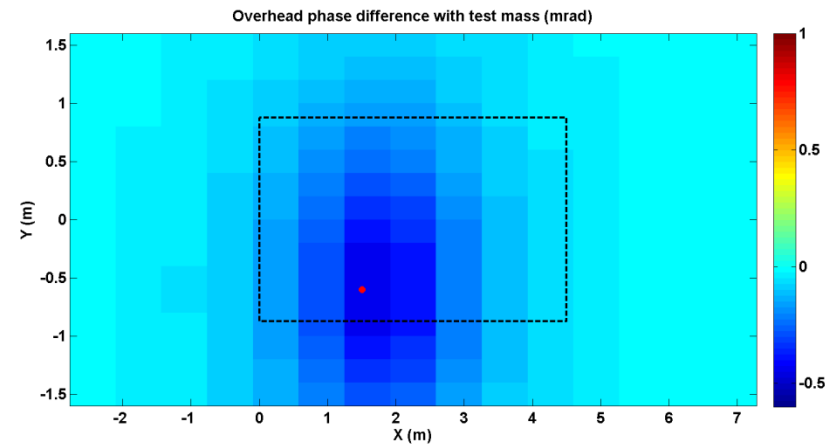
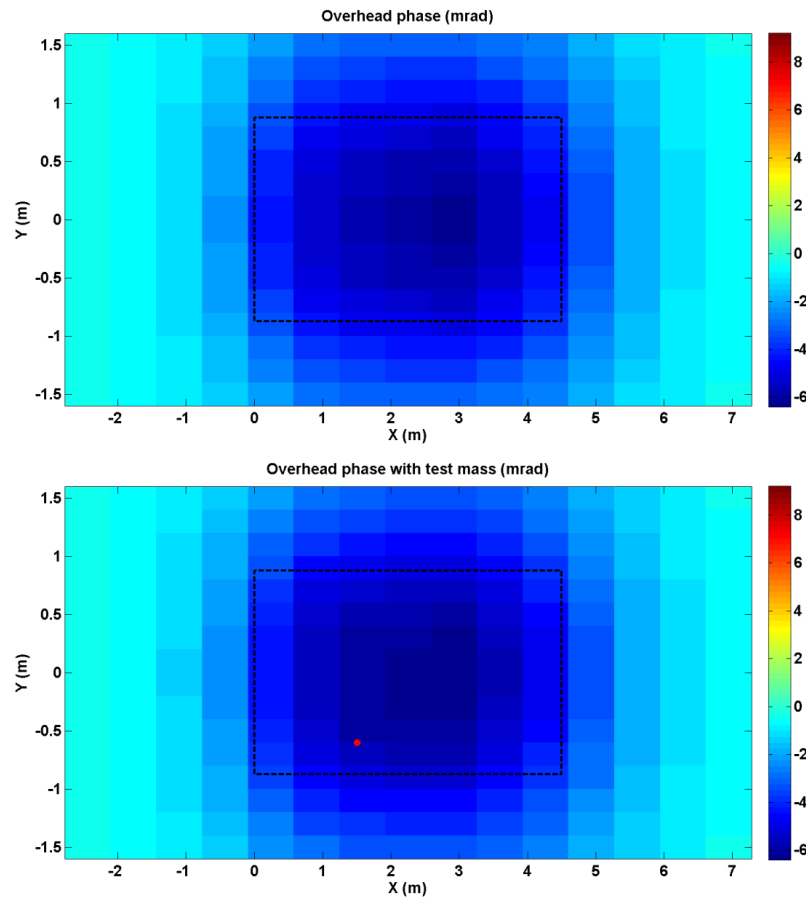**Red dot is test mass position (projected)**

Driver side phase (mrad)

Driver side phase (mrad)

Driver side phase with test mass (mrad)

Driver side phase difference with test mass (mrad)

Dotted line is outline of vehicle

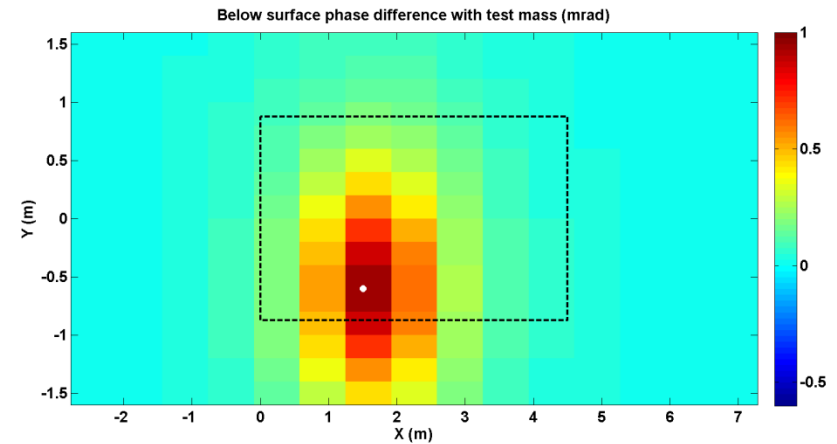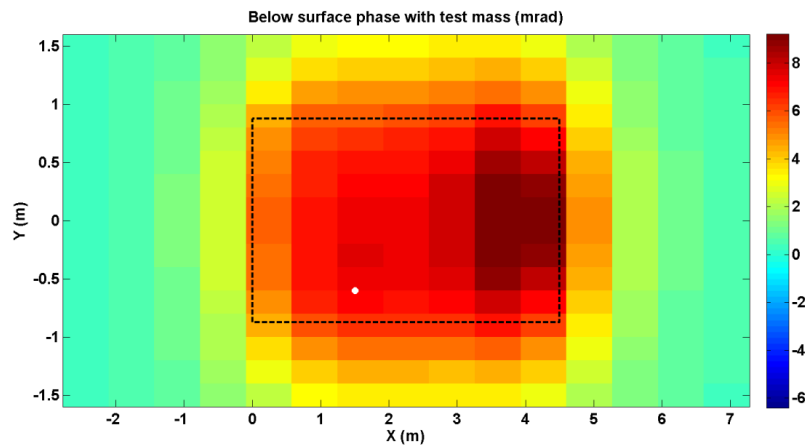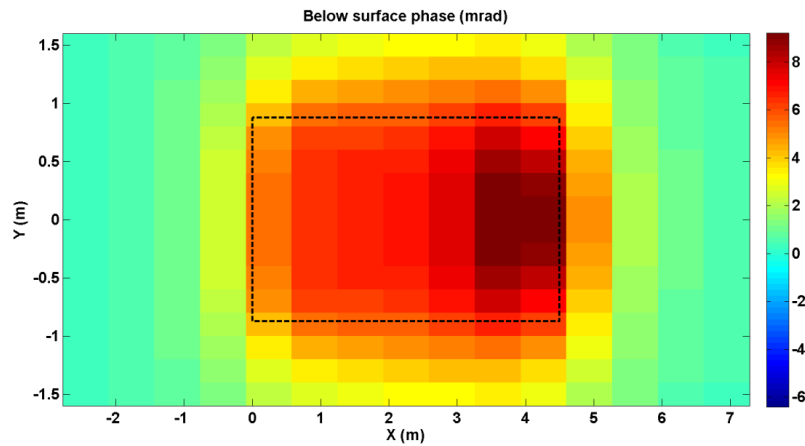**Red dot is test mass position (projected)**

Overhead phase (mrad)

Dotted line is outline of vehicle

Red dot is test mass position (projected)

Below surface phase (mrad)


Dotted line is outline of vehicle

White dot is test mass position (projected)

Observations from phase differences

- Maximum response occurs for sensors below vehicle (0.95 mrad)

- Maximum responses for sensors above and below vehicle occur directly above/below the test mass

- Maximum response for passenger side (-0.56 mrad) occurs for sensor 0.5 m above test mass height

- Possible to triangulate test mass position using node of response for passenger side, maximum for below surface sensor, and maximum along x

Consider mass model derived for actual vehicle

- **Point mass model of Yaris**
- **Total mass: 1066 kg, 1601 points**
- **Place sensor lines at 20 cm intervals in a box surrounding the model**
  - **Upper box surface at height of 2 meters**
  - **Lower box surface at 0.6 meters below ground level**
  - **Sides of box at +/- 1.5 meters**
  - **All surfaces approximately 60 cm from sides**
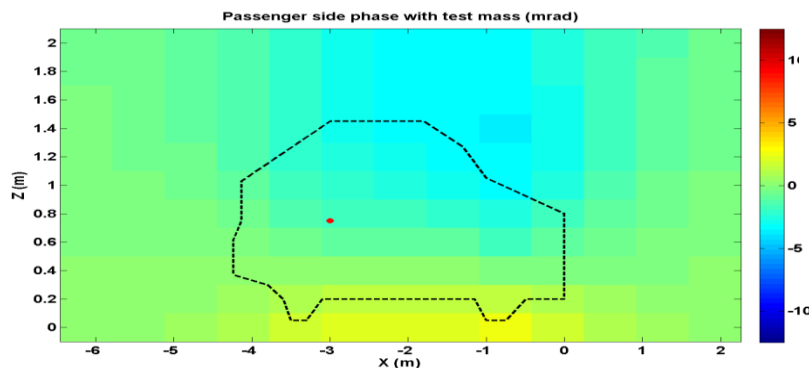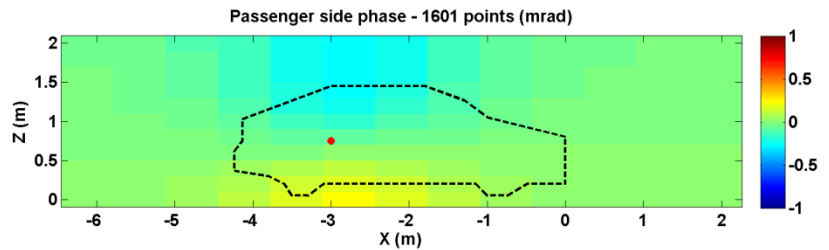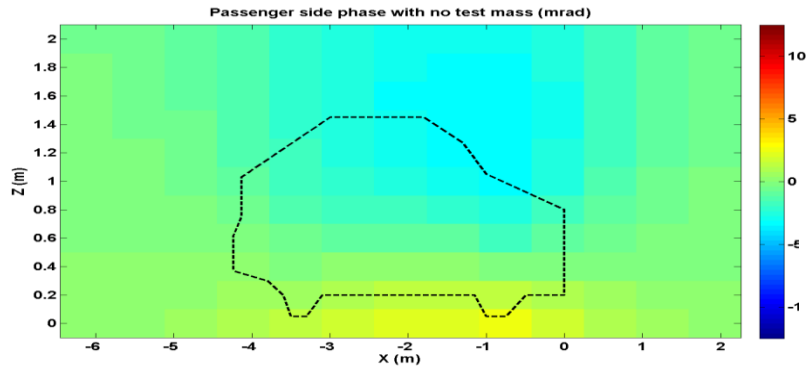 - **Sensor line sampling interval equivalent to 2 samples per second with vehicle moving at 3 MPH**
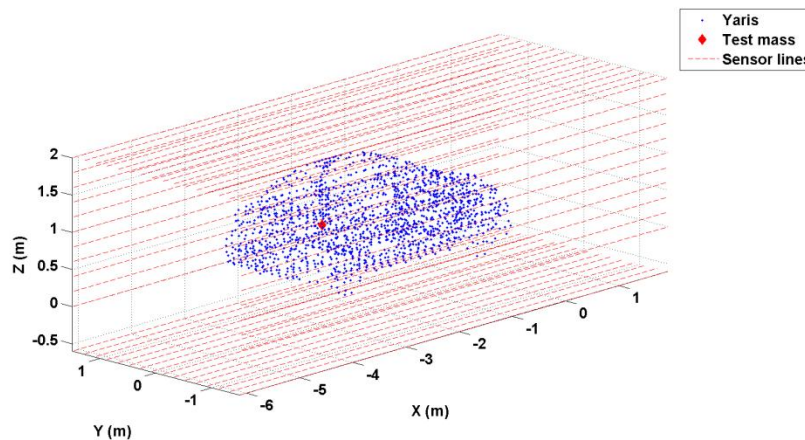
Gravimeter model parameters:

- Launch velocity: 1.84 m/s upward
- Sensor interrogation time: 0.15 s
- Vehicle velocity: 3 MPH in +x direction
- Vertical sensors

Test mass position (x,y,z):
(-3, 0, 0.75) meters
Back center of model
65 kg

Passenger side phase (mrad)

Passenger side phase with no test mass (mrad)

Passenger side phase - 1601 points (mrad)

Passenger side phase with test mass (mrad)

Dotted line is outline of vehicle
Red dot is test mass position (projected)

Overhead phase (mrad)

Overhead phase with no test mass (mrad)

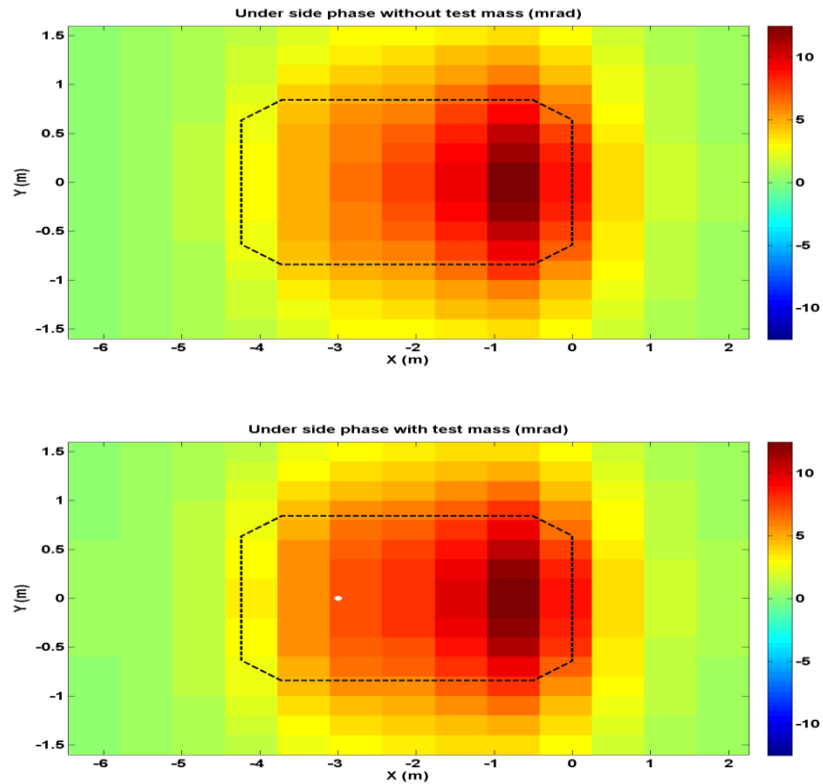Overhead phase with test mass (mrad)

Overhead phase - 1601 points (mrad)
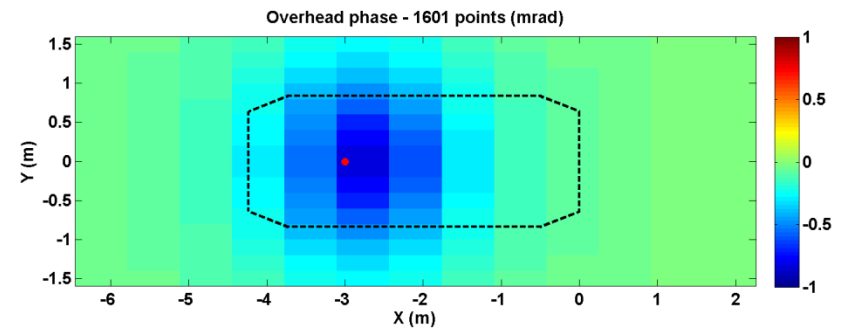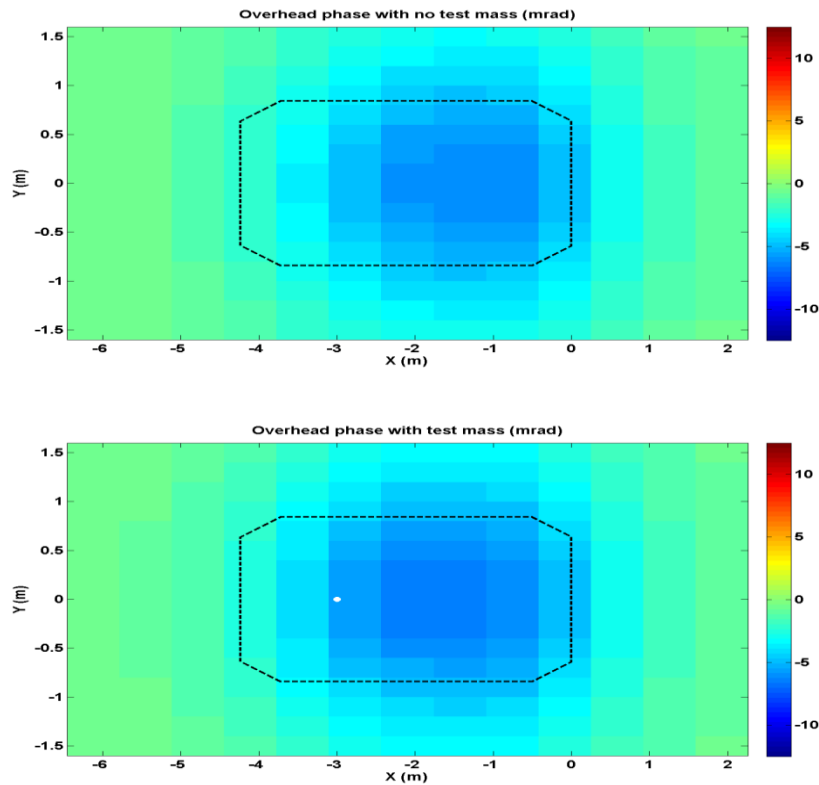
Dotted line is outline of vehicle
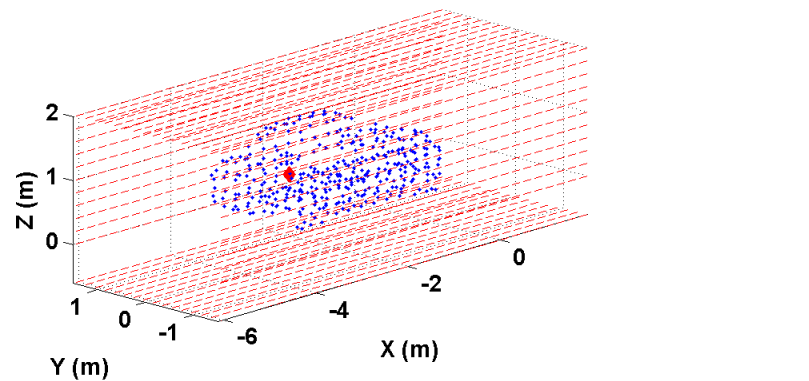**White dot is test mass position (projected)**

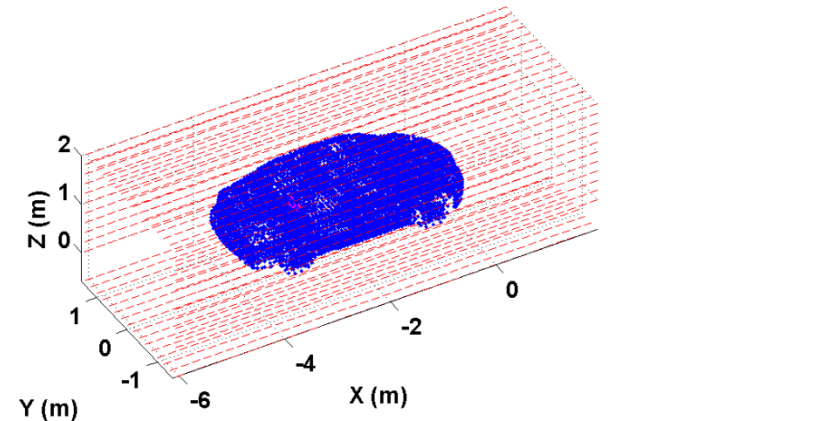# Below surface phase (mrad)

Dotted line is outline of vehicle
White dot is test mass position (projected)

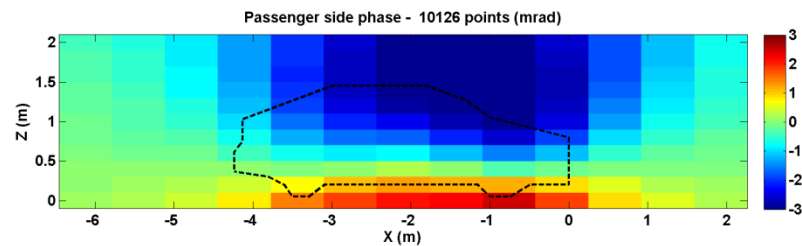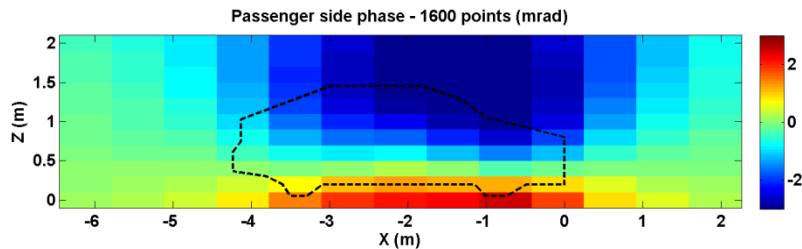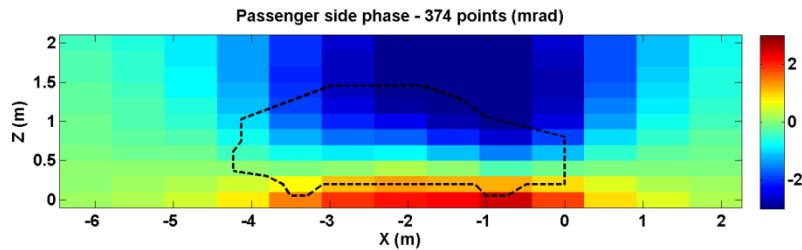# Compare with 374 point and 10126 point models

374 point model

	Yaris
•	Yaris
♦	Test mass
- - -	Sensor lines

10126 point model

•	Yaris
♦	Test mass
- - -	Sensor lines

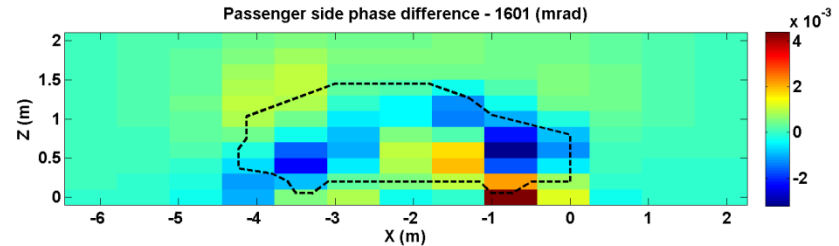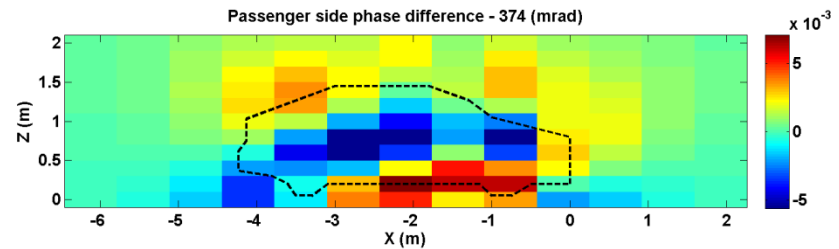**Lawrence Livermore National Laboratory**

Passenger side phase (mrad)

Phase distributions at different model resolutions

Difference between lower resolution models and high resolution (10126 point) model

Passenger side phase - 374 points (mrad)

Passenger side phase difference - 374 (mrad)

Passenger side phase - 1600 points (mrad)

Passenger side phase difference - 1601 (mrad)

Passenger side phase - 10126 points (mrad)

Maximum phase differences
374 points: 0.0071 mrad
1601 points: 0.0044 mrad

Overhead phase (mrad)

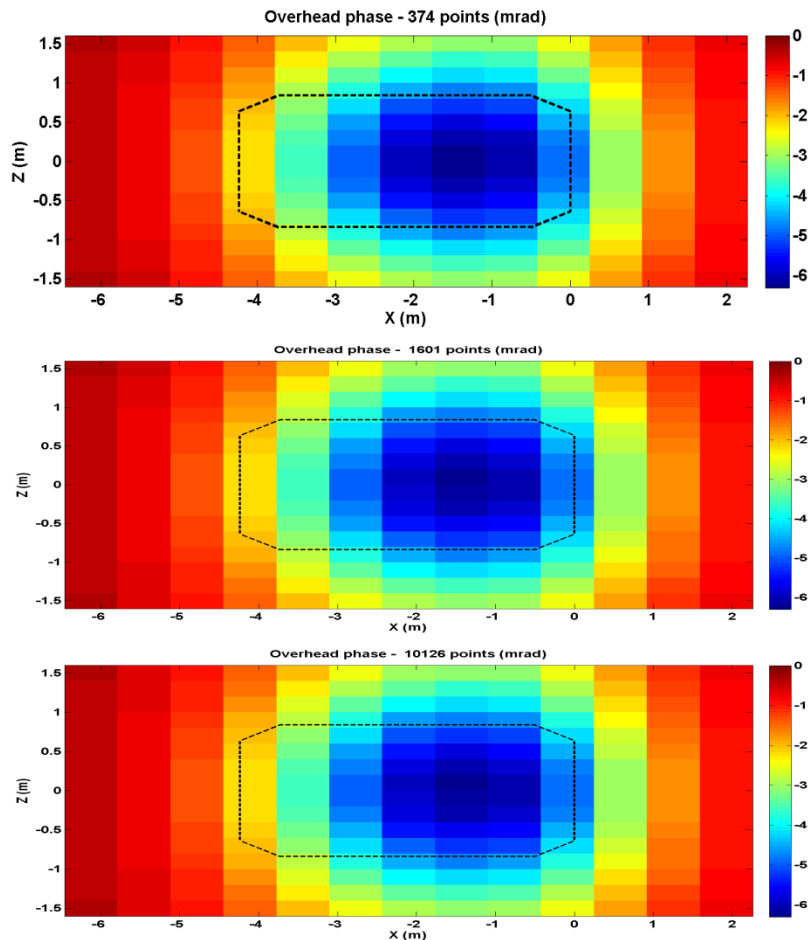**Phase distributions at different model resolutions**

Difference between lower resolution models and high resolution (10126 point) model
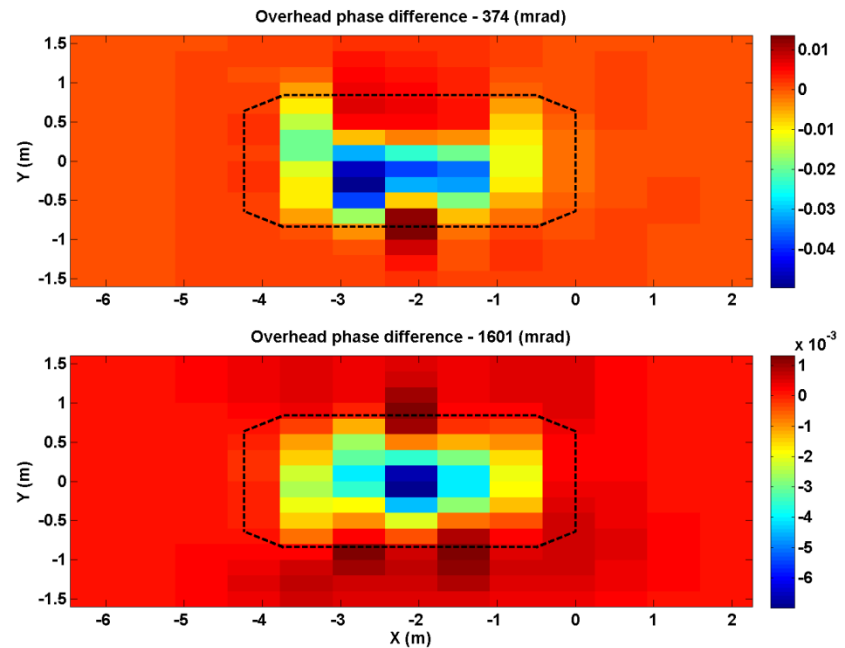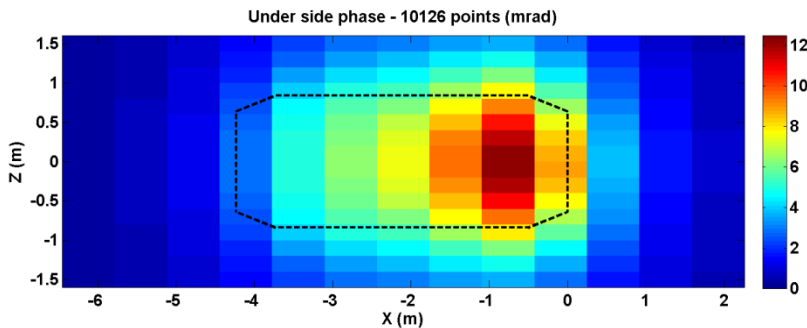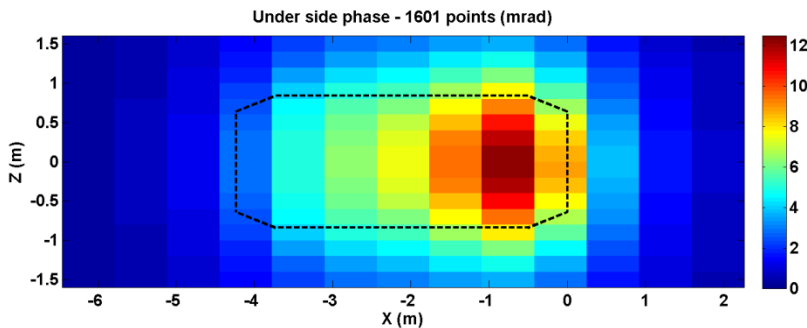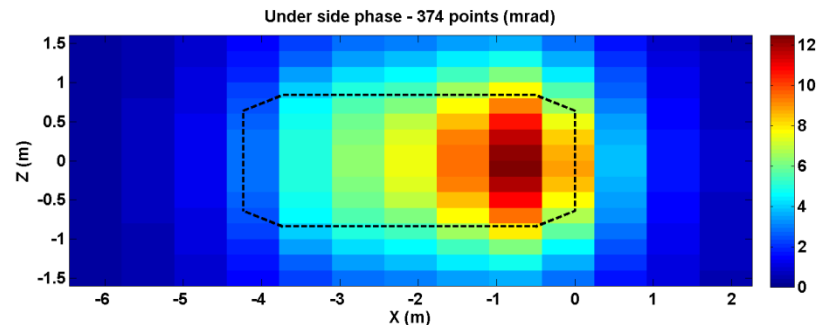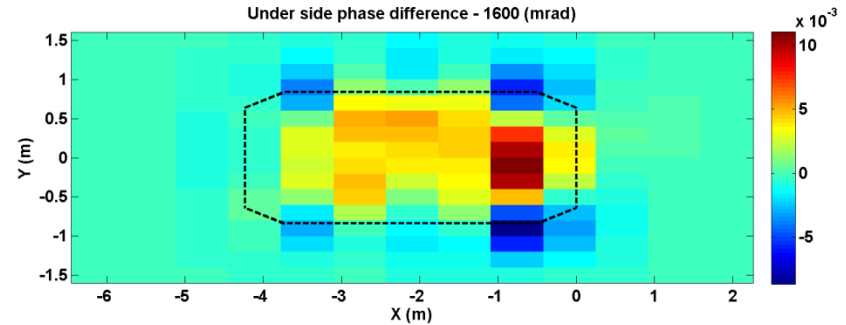

Maximum phase differences
374 points: 0.050 mrad
1601 points: 0.0070 mrad

Below surface phase (mrad)

Phase distributions at different model resolutions

Under side phase - 374 points (mrad)

Under side phase - 1601 points (mrad)

Under side phase - 10126 points (mrad)

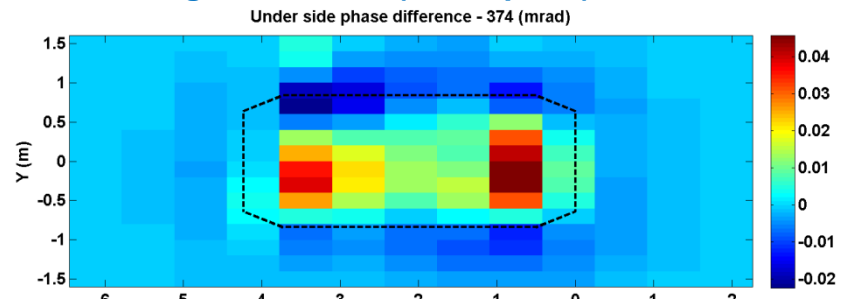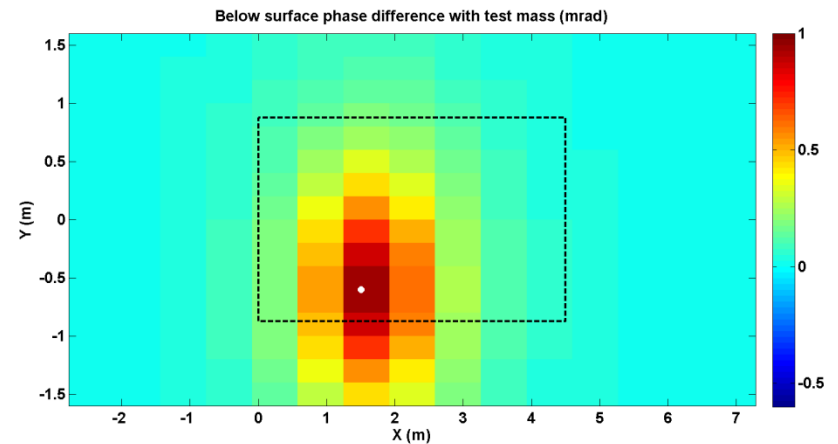**Difference between lower resolution models and high resolution (10126 point) model**

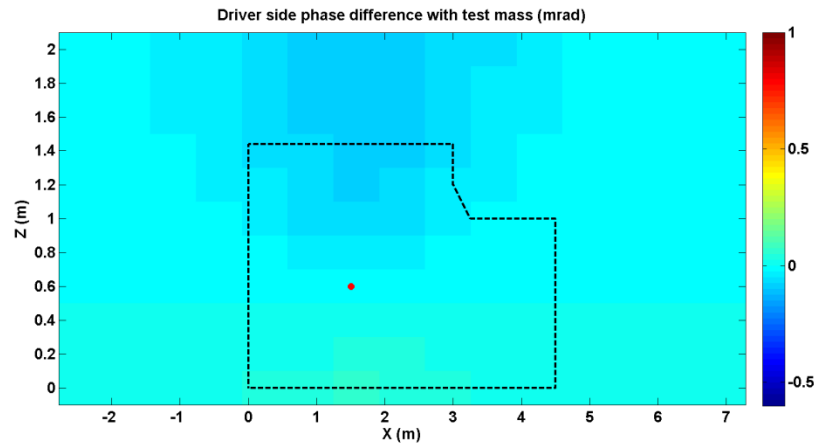Under side phase difference - 374 (mrad)

Under side phase difference - 1600 (mrad)

Maximum phase differences
374 points: 0.046 mrad
1601 points: 0.011 mrad

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Conclusions

- Responses of sensors to point masses of 65 kg are ~10% of response to vehicle alone

- Highest response occurs for sensors placed nearest the additional mass, typically below the vehicle

- Point mass model for vehicle is insensitive to number of point masses to represent vehicle mass distribution

BACKUPS

Phase differences (with/without test mass)

Driver side phase difference with test mass (mrad)

Overhead phase difference with test mass (mrad)

Passenger side phase difference with test mass (mrad)

Below surface phase difference with test mass (mrad)
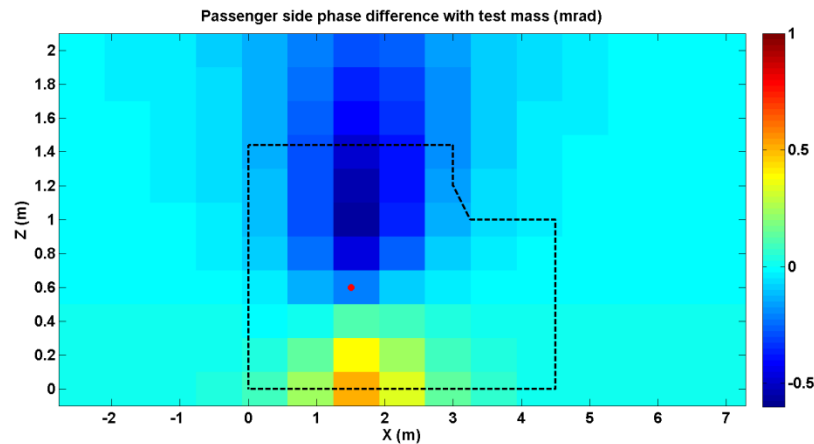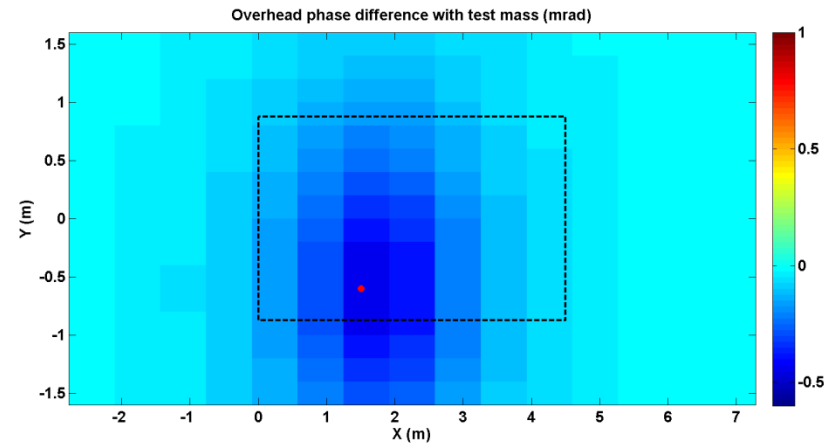
Dotted line is outline of vehicle
Red/white dot is test mass position
(projected)